LA-UR-21-23127

Title:	Image Station Use Examples from DARHT
Author(s):	Jaworski, Michael Andrew
Intended for:	Working group meeting and distribution.
Issued:	2021-04-01

Image Station Use Examples from DARHT

M.A. Jaworski
Los Alamos National Laboratory

ASD-Scorpius Downstream Transport Meeting
January 29, 2021

UNCLASSIFIED

Outline of Material

- The beam envelope equation for tuning
- Optical Transition Radiation (OTR)
- Solenoid scan method for beam identification
- Pepper-pot method for beam identification
- Beam-target studies via gated imaging

A word about sources…

“Immature artists imitate. Mature artists steal.”

-Various attributions (Eliot, Picasso, Trilling, others)*

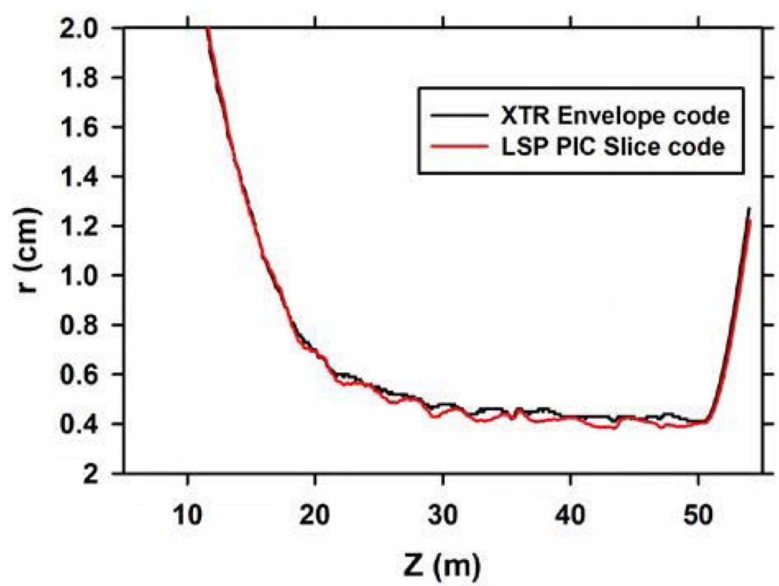
- J-6 scientists are the local experts on these techniques (DC Moir, C Ekdahl, M Schulze)
- This talk is mostly a summary of what they’ve been doing for years (and I’ve just been learning)

*Quote Investigator https://quoteinvestigator.com/2013/03/06/artists-steal/

Validated theory enables design

- Envelope equation describes beam radius evolution
- Various derivations either from beam moments[1] or paraxial equations[2]
- Use for LIA analysis developed to high degree by P. Allison in xtr[3]
- Checked against various PIC codes over the years[4]

$$r_m'' + \underbrace{\boxed{\frac{\gamma' r_m'}{\beta^2\gamma}}}_{\text{Accel. damping}} + \underbrace{\boxed{\frac{\gamma'' r_m}{2\beta^2\gamma}}}_{\text{Gap accel.}} + \underbrace{\boxed{\left(\frac{qB}{2mc\beta\gamma}\right)^2 r_m}}_{\text{Sol. focus}} - \underbrace{\boxed{\left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{r_m^3}}}_{\text{Angular momentum}} - \underbrace{\boxed{\frac{\epsilon_n^2}{\beta^2\gamma^2 r_m^3}}}_{\text{Emittance}} - \underbrace{\boxed{\frac{K}{r_m}}}_{\text{Self-fields}} = 0.$$



Ekdahl, et al., IEEE TPS (2017)

[1]Lee and Cooper, Part. Accel. 7 (1976) 83.
[2]cf Reiser "Theory and Design…" 2008. and Humphries "Charged Particle Beams" 2002.
[3]Allison, LA-UR-01-6585 (2001)
[4]Ekdahl, et al., IEEE Trans. Plasma Sci. 45 (2017) 2962.

Radius, convergence, and emittance are key parameters in the envelope equation

$$r_m'' + \frac{\gamma' r_m'}{\beta^2\gamma} + \frac{\gamma'' r_m}{2\beta^2\gamma} + \left(\frac{qB}{2mc\beta\gamma}\right)^2 r_m - \left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{r_m^3} - \frac{\epsilon_n^2}{\beta^2\gamma^2 r_m^3} - \frac{K}{r_m} = 0.$$

- Equation is second order and requires initial conditions **R_0**, **dR_0/dz** and **ε_n** to solve
- Constant emittance is assumed, though models exist to describe growth
- B-fields and acceleration gaps are considered knowns with energy & current
- Equation is symmetric in z: can be solved “backwards”
- Uncertainties propagate or may only weakly determine beam properties far away from measurement point

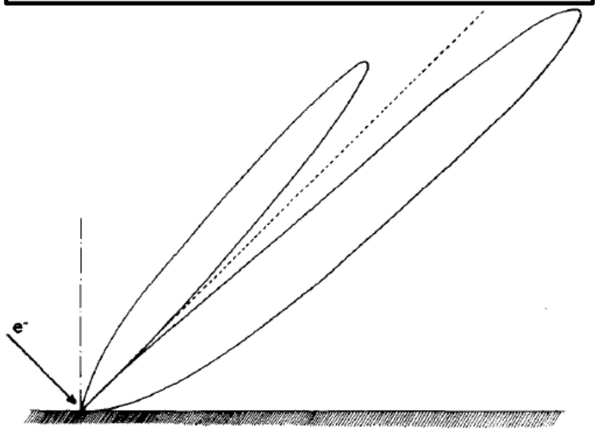
Outline of Material

- The beam envelope equation for tuning
- Optical Transition Radiation (OTR)
- Solenoid scan method for beam identification
- Pepper-pot method for beam identification
- Beam-target studies via gated imaging

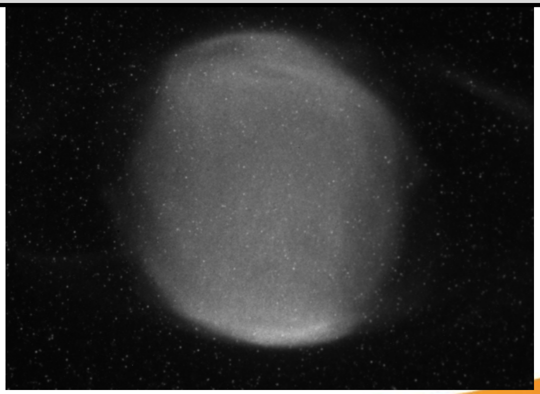
Optical transition radiation is produced where electrons transit material boundaries

- OTR can be considered a special form of Cerenkov radiation[1,2]
- Radiation emitted when const. velocity particle traverses materials with different dielectric constants
- Simple and complex uses exist in literature
  - "Near-field" images source location and intensity
  - "Far-field" can extract convergence and emittance

Radiation Pattern, γ=10 [1]



DARHT-2 ISC Image (2019)

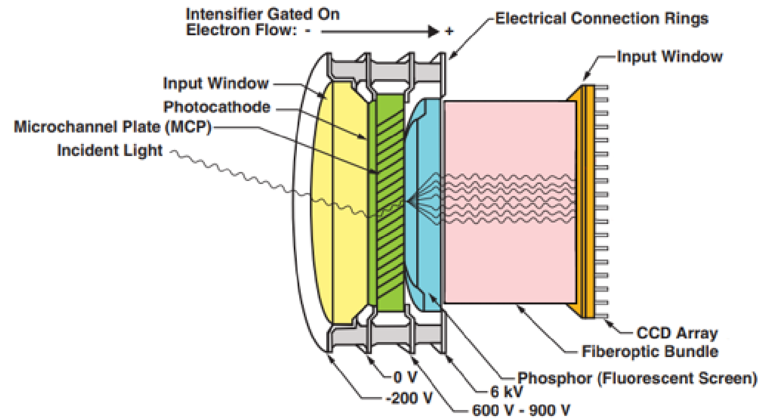


[1]Wartski, et al., J. Appl. Phys. 46 (1975) 3644.
[2]Fiorito and Rule, Conf. Proc. Beam Instrum. Workshop (1994) 21.

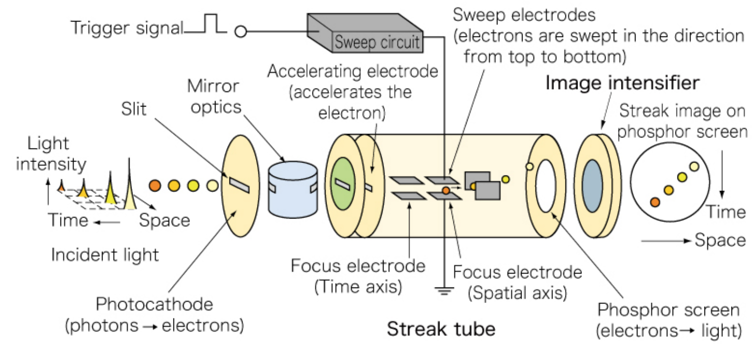
Time-resolved or gated imaging is critical to these diagnostics

- Beam dynamics and target phenomena evolve on ~ns time scale
- Intensified imagers amplify photon-starved signals
- Gated cameras retain 2D information for a single time window
- Streak systems can provide continuous, time-resolved 1D "slice"

Intensified CCD Operating Principle



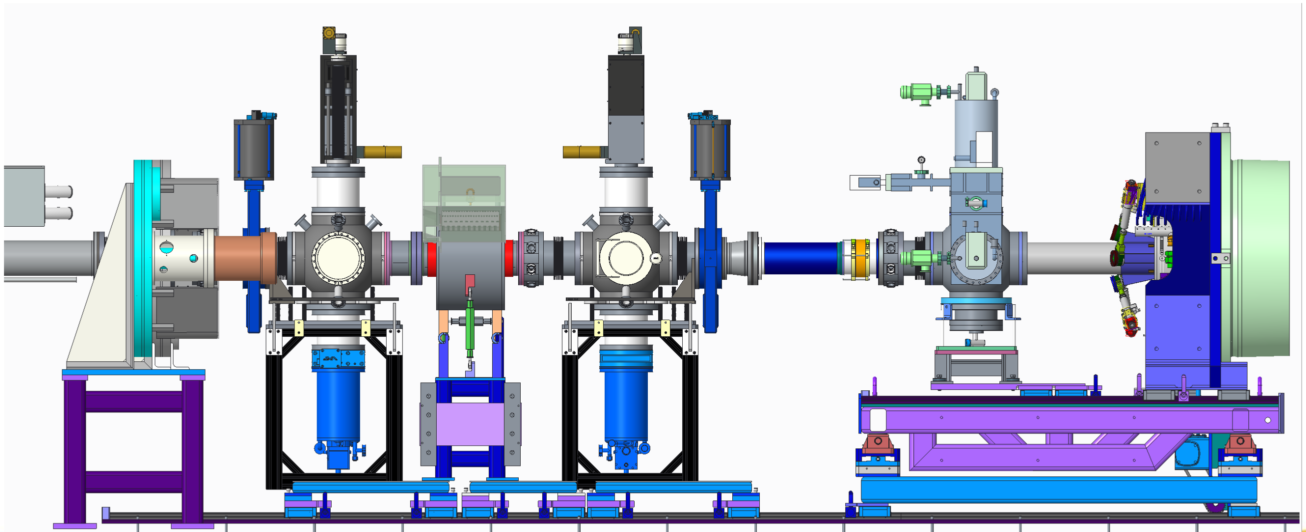
Streak Camera Operating Principle

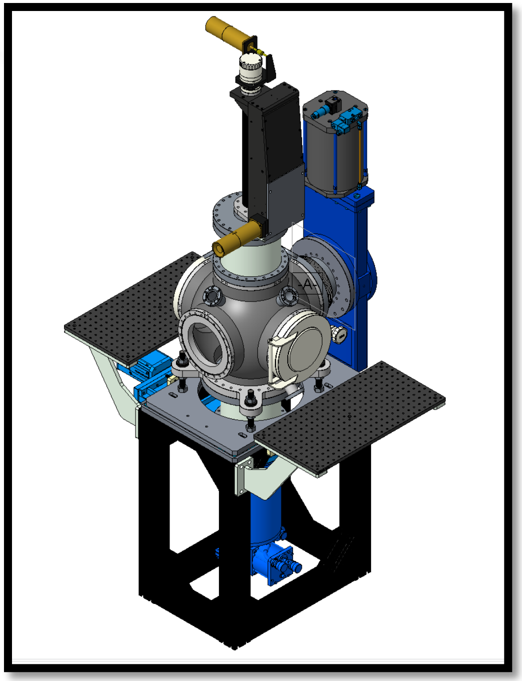


[1]https://www.princetoninstruments.com/learn/camera-fundamentals/iccd-and-emiccd-basics
[2]https://www.hamamatsu.com/us/en/product/photometry-systems/streak-camera/operating-principle/index.html

OTR alone at two locations can provide R and R’

- Direct measure of R with known z between locations
- Single camera with mirrors or
- Simultaneous measurements (with caveats for foil focusing + scattering)





Outline of Material

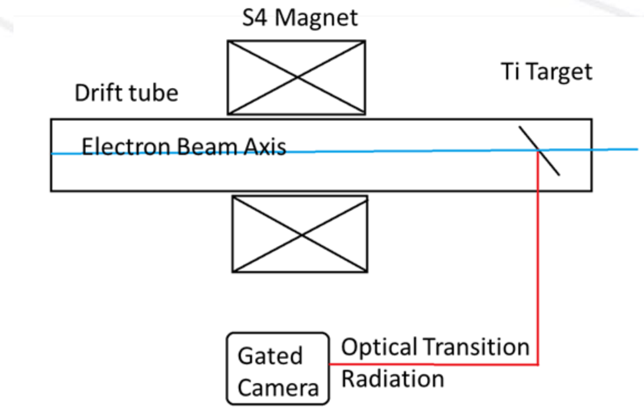
- The beam envelope equation for tuning
- Optical Transition Radiation (OTR)
- Solenoid scan method for beam identification
- Pepper-pot method for beam identification
- Beam-target studies via gated imaging

OTR + solenoid scans can extract R, R’, and ε_n

$$r_m'' + \left(\frac{qB}{2mc\beta\gamma}\right)^2 r_m - \frac{\epsilon_n^2}{\beta^2\gamma^2 r_m^3} - \frac{K}{r_m} = 0$$

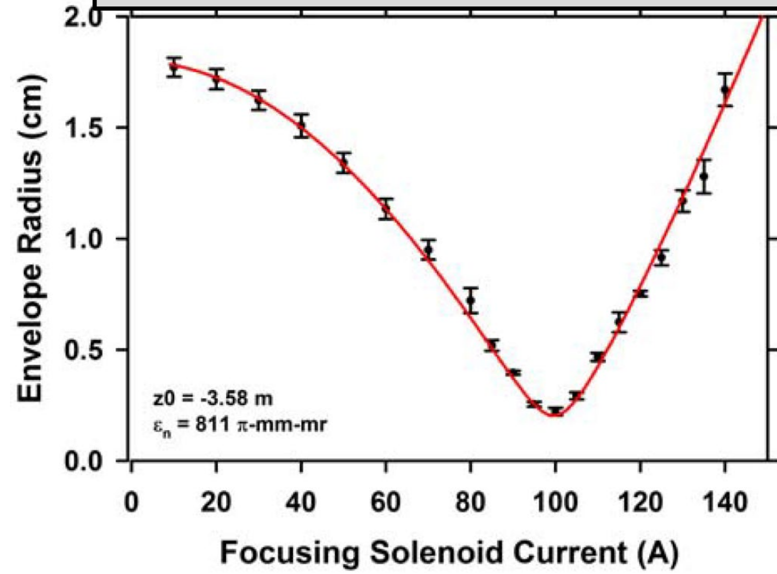
- Envelope through magnetic field can be solved for entrance conditions (R, R’, ε_n)
- Scan in magnetic field changes waist location: sum of data provides unique solution to three variables
- Zeroth order consideration: don’t destroy the target and avoid beam-target interaction effects!
  - Long focal length increases spot size
  - Short pulses and gating early in the pulse reduces light-ion effects

Typical Configuration



Moir and Allison, LA-UR-21-21386

DARHT-2 Solenoid Scan Result

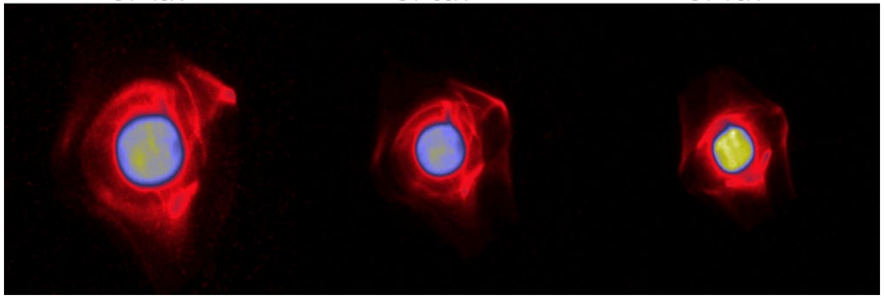


Ekdahl, et al., IEEE TPS (2017)

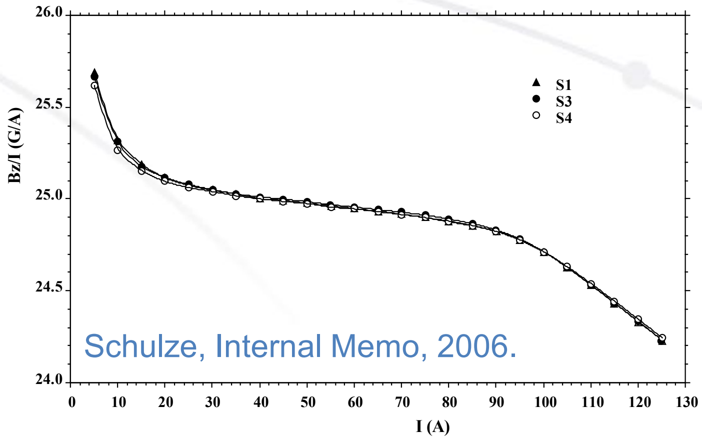
Additional corrections and interpretations

- Magnetic field is assumed “known” but non-linear excitation affects analysis
- High-contrast imaging can reveal beam halo and indicate larger **ε_n** (Moir and Allison, LA-UR-21-21386)
- Spherical aberrations can modify results as well (Schulze LA-UR-20-24545)

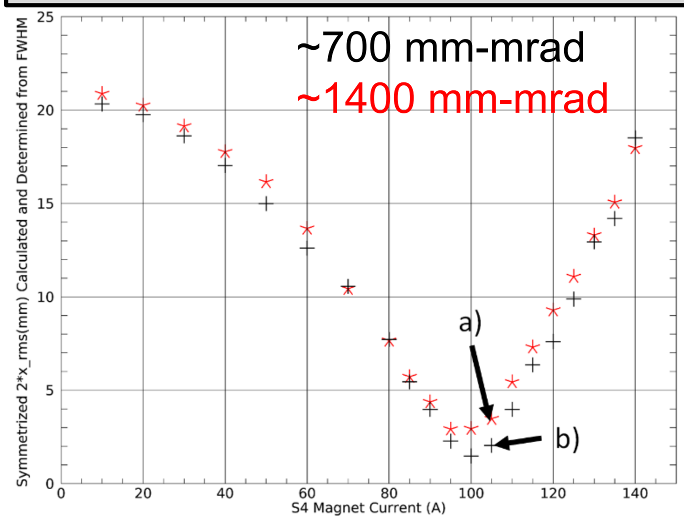
Beam Halo



Magnet Excitation Fall-off



Solenoid Scan w/ and w/o Halo



Moir and Allison, LA-UR-21-21386

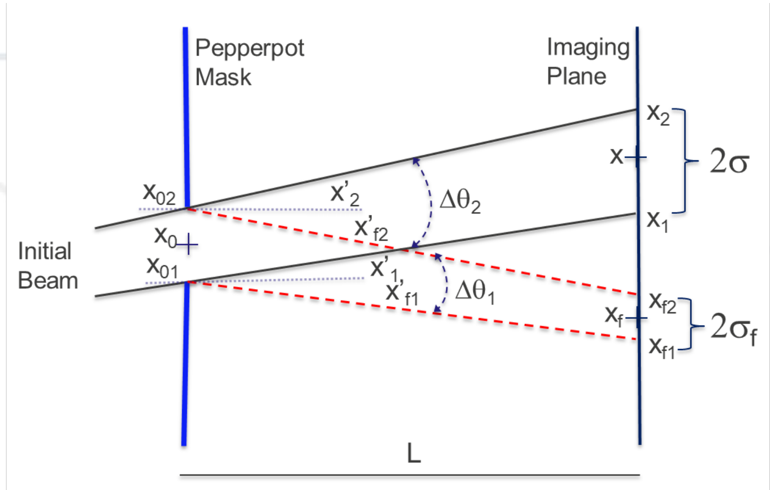
UNCLASSIFIED

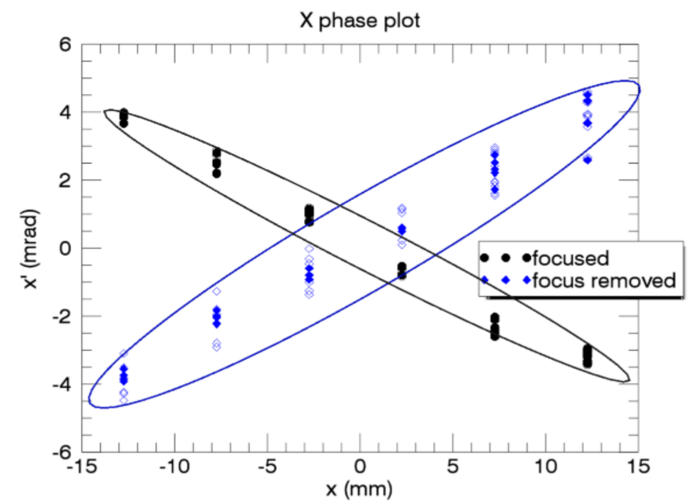
Outline of Material

- The beam envelope equation for tuning
- Optical Transition Radiation (OTR)
- Solenoid scan method for beam identification
- Pepper-pot method for beam identification
- Beam-target studies via gated imaging

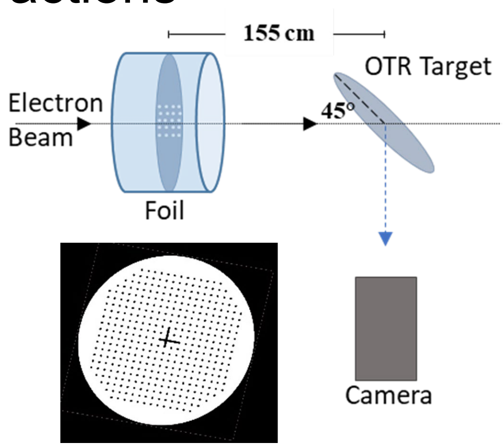
Pepper-pot diagnostic method can extract ε_n of the beam

- Thin pepper-pot creates contrast by scattering portions of the beam
- Beamlet size relative to mask gives emittance
- *In principle:* eliminates need for dual-imaging and reduces beam-target interactions





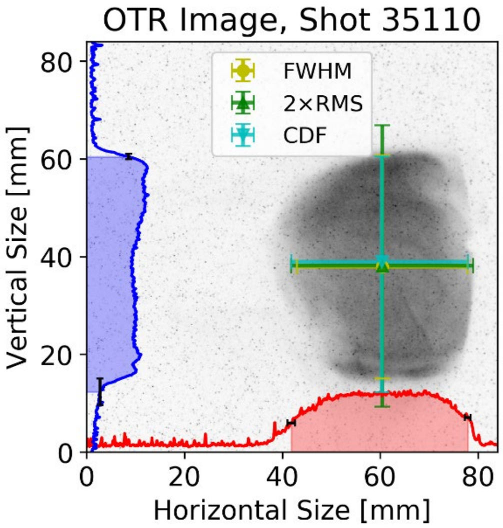
in π-mm-mrad	ε_x	ε_y
Focused	147	306
Corrected	226	415

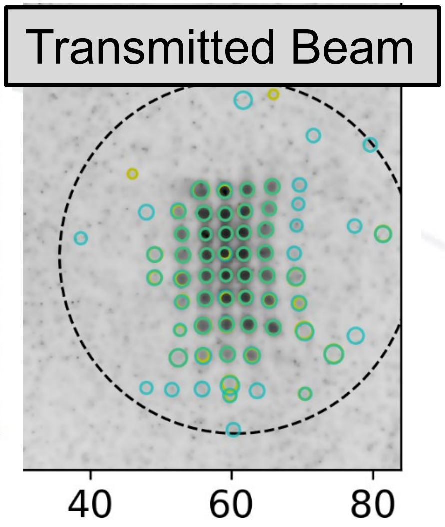


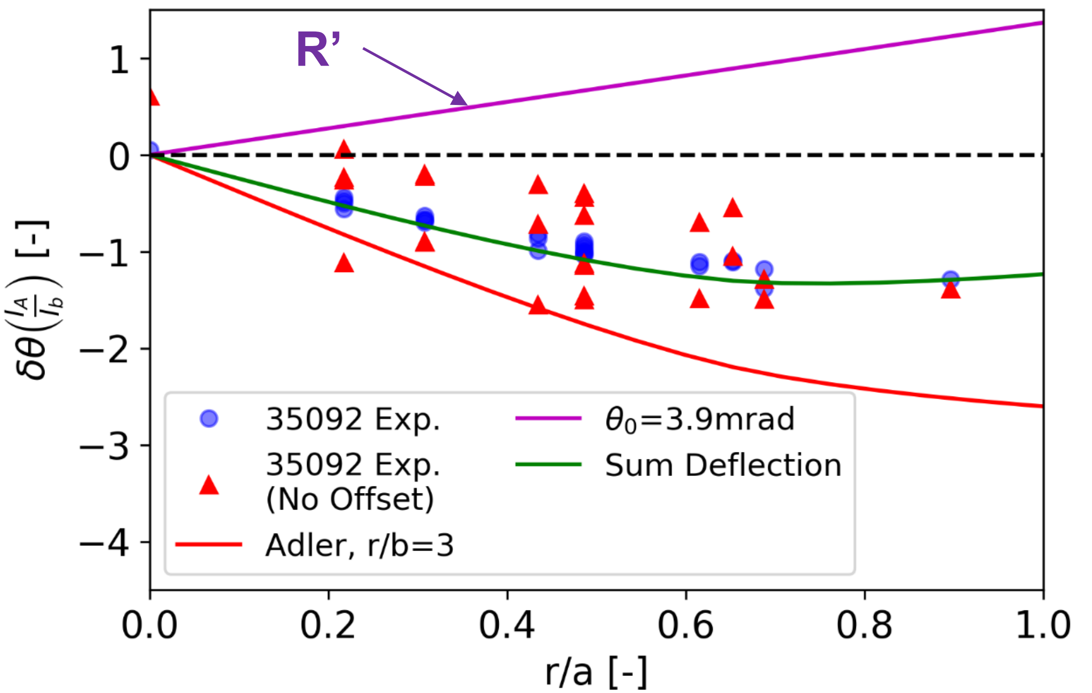
Schultz, et al., Proc. NAPAC 2019

Single pepper-pot can also provide R, and R' measurements

- **R** can be determined from counting mask dots (low resolution)
- **R'** from beam distortion and foil-focusing
- **ε_n** from spot-size analysis
- *Not really this simple: analysis still in development!*





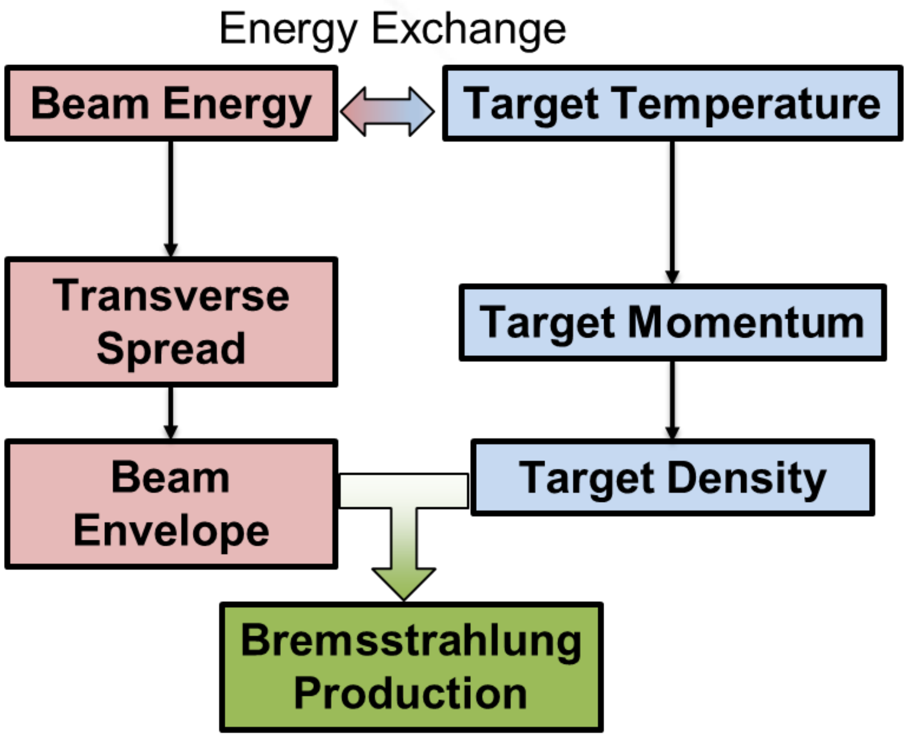


Outline of Material

- The beam envelope equation for tuning
- Optical Transition Radiation (OTR)
- Solenoid scan method for beam identification
- Pepper-pot method for beam identification
- Beam-target studies via gated imaging

Multi-pulse targets have intrinsic differences to single-pulse targets

- Target is evolving in time
- Input beam energy drives expansion
- X-ray output produced by co-incidence of beam and target
- Plume imaging provides insight into target state during evolution



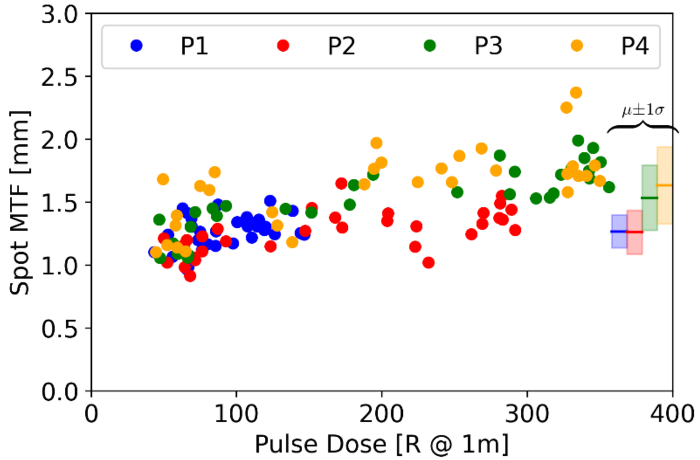
Beam evolution in target depends on target properties

- Historical database indicates late-time pulses are dissimilar to early times

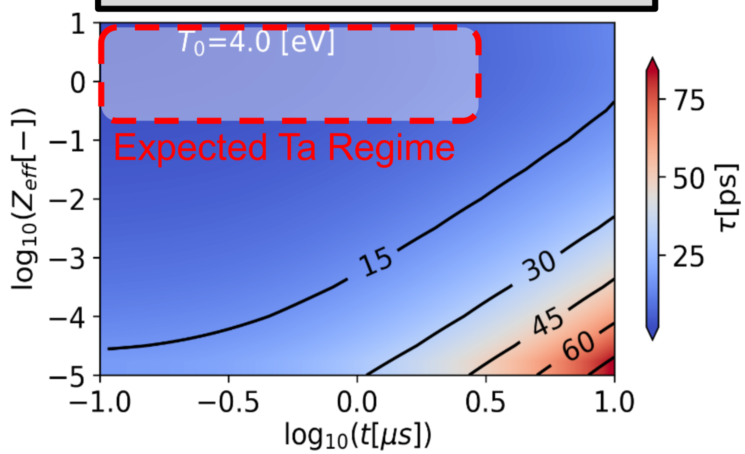
- Beam-plasma interactions vary from macro- to micro-scale
  - Magnetic pinch effects evolve with magnetic diffusion time (density, temperature, degree of ionization)[1]
  - Beam-plasma instability growth rate depends strongly on target density[2,3]

- Understanding the target is integral to understanding our x-ray source

DARHT-2 Historical Performance



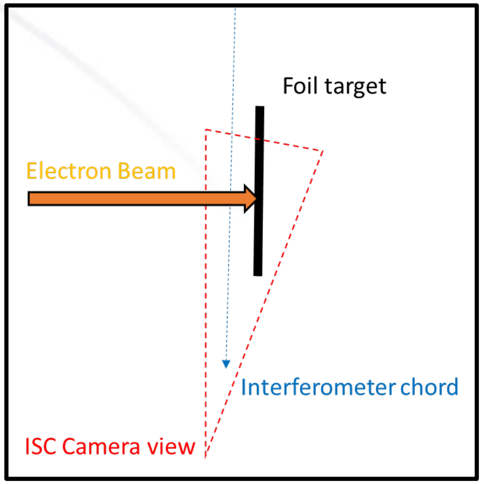
Oblique Instability Growth Rate

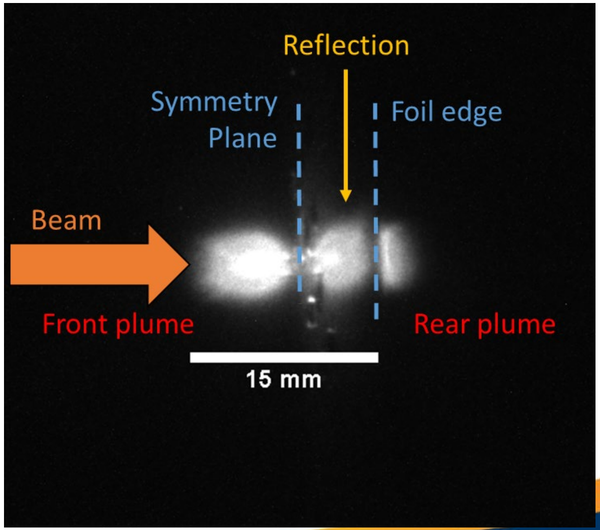


[1]cf. Humphries "Charged Particle Beams" 2002.
[2]Bret, et al., Phys. Plasmas 17 (2010) 120501.
[3]Jaworski, et al., APS-DPP 2019, LA-UR-19-30587.

Initial experiments conducted with single pulse driving expansion

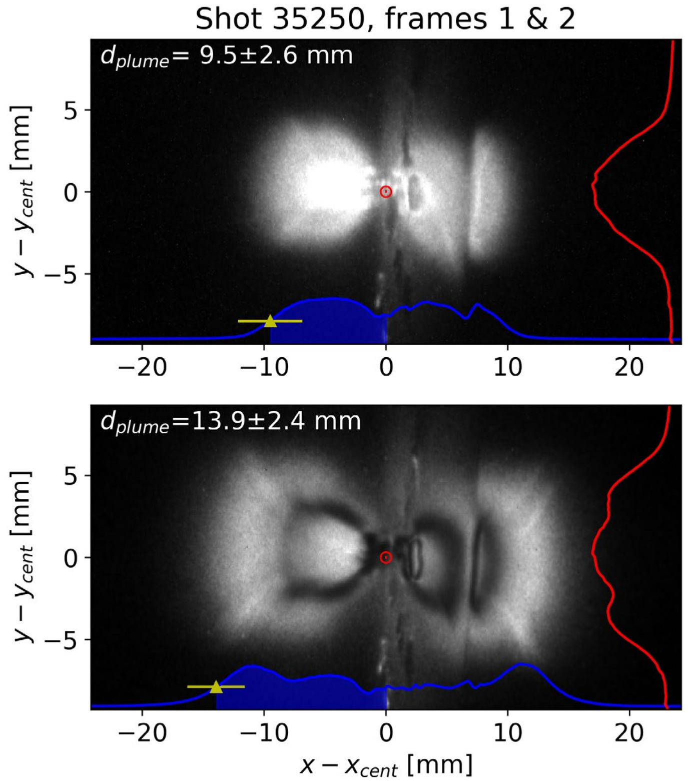
- Camera positioned off-normal to avoid other optics
  - Angle is 5.5° and accounted for in analysis
  - Reflected image of plume is visible
- Timing of camera gate varied on identical tune
- Some camera artifacts present, but not used in analysis
- 250μm Mo foil target





Data reduction largely automated and includes uncertainty estimates

- Velocity extracted from each frame
  - Velocity = distance/time
  - Timing uncertainty based on earlier experiments scanning pulse (+/-10ns to t=0)
- Distance determined from center of plume (symmetry point)
  - Assumes photon intensity = material
  - Edges found at half-maximum intensity
- Uncertainty from multiple sources:
  - Intensity slope at half-max
  - Shifts of calculated center between frames
  - +/-1° viewing angle
  - Timing uncertainty



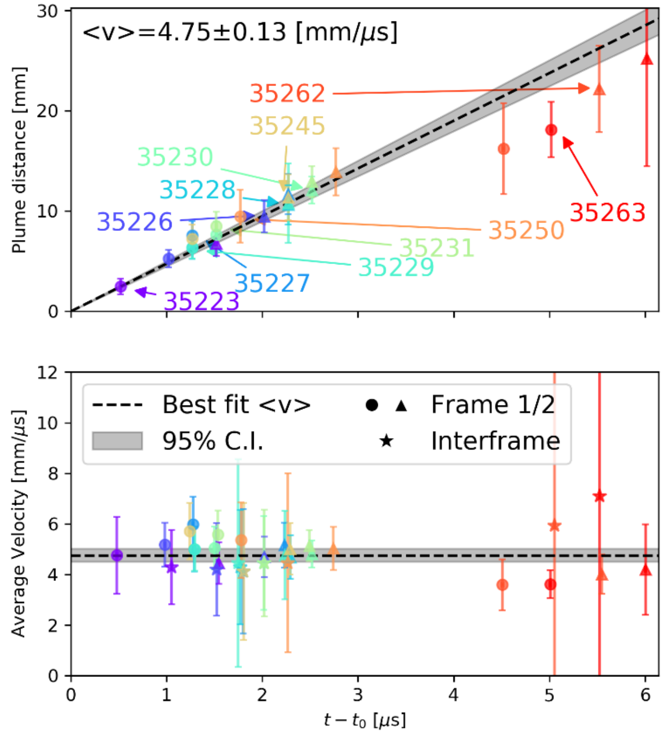
Plume expands at 4.75 mm/μs in this experiment

- From database select shots with:
  - S4 magnet = 100A, P1=40ns, P2=0ns
  - Frame 1 timing provides scan
- Constant velocity expansion model fit to data
  - Alternative models not explored
  - Potential deceleration late in time

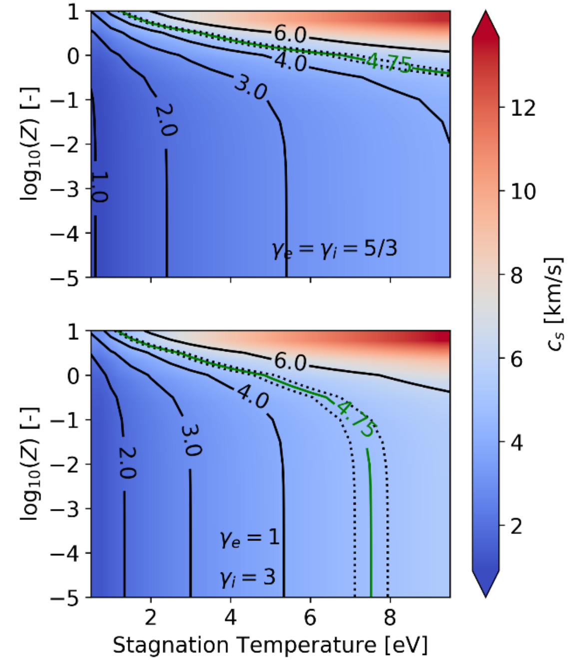
Ion Acoustic Speed

$$c_s = \left(\frac{\gamma_e Z_{eff} k T_e + \gamma_i k T_i}{M_i} \right)^{1/2}$$

Measured Velocities

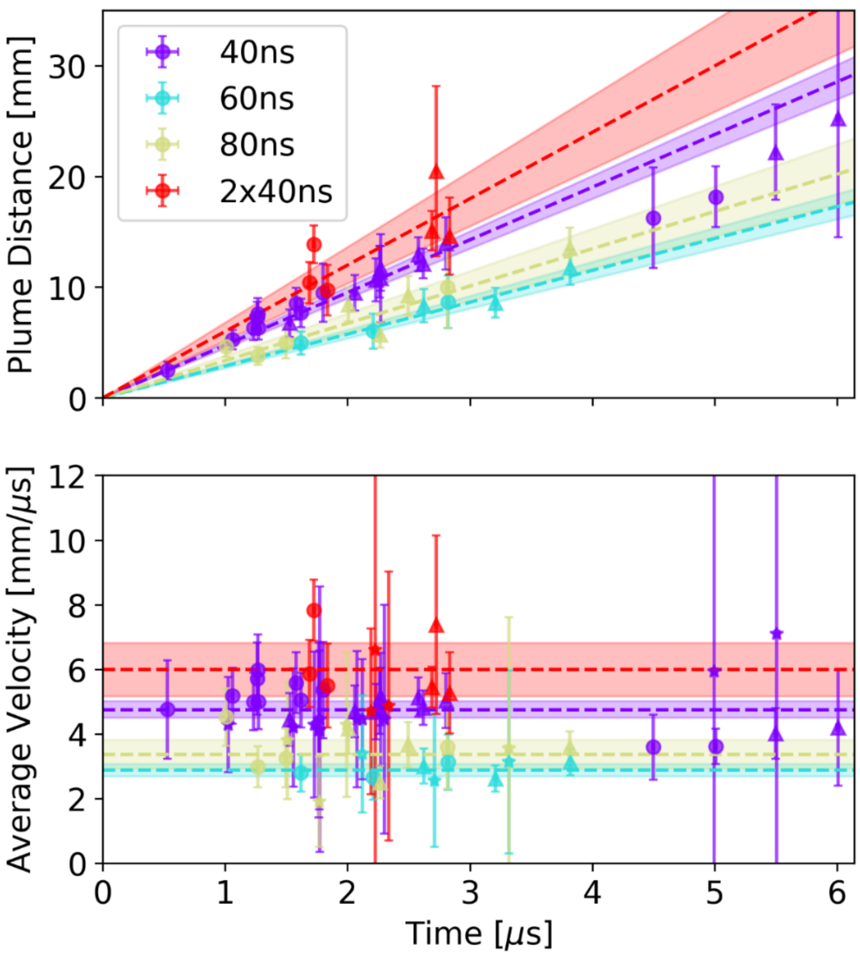


Mo Sound Speed



Plume experiments examined four pulse formats

- 40, 60, 80, and 2x40ns experiments conducted
- Data indicate velocity relatively constant in all experiments
- Unexpected variations observed as pulse-length increases

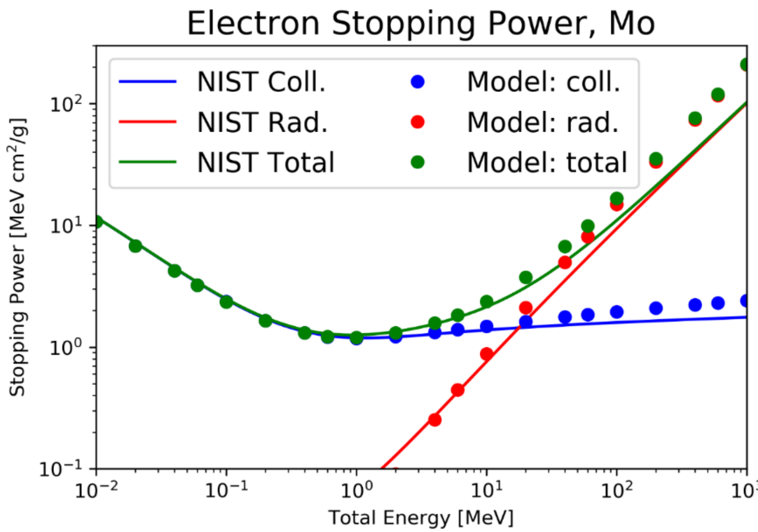


E-beam parameters connect to thermodynamic model via energy density

- Spot radius, current, and pulse-length determine energy density
- Collisional stopping power only weakly dependent on energy
- Known parameters and material means radius can be extracted from known energy density

$$E_{dep} = \rho_{target} \frac{I_{beam}}{A_{beam}} \left.\frac{\mathrm{d}E}{\rho \mathrm{d}x}\right|_{coll.} \tau_{pulse}$$

$$r_{beam} = \left[\rho_{target} \frac{I_{beam}}{\pi E_{dep}} \left.\frac{\mathrm{d}E}{\rho \mathrm{d}x}\right|_{coll.} \tau_{pulse} \right]^{1/2}$$



Mass, momentum, and energy balance used to evolve target material

- Mass balance: constant number of particles in the plume
- Momentum balance: change in velocity determined by pressure and mass in plume
- Energy balance: total energy (e_{int}+e_{kin}) is conserved except during heating
- Entropy constraints provide sanity-check on expansion
- **Real-gas thermodynamic model developed to describe pressure/temperature during expansion**

$$\left\{ \begin{array}{l} N_0 = n_0 h_0 \pi r_0^2 = n_0 V_0 \\ n(t) = \frac{N_0}{V(t)} \end{array} \right.$$

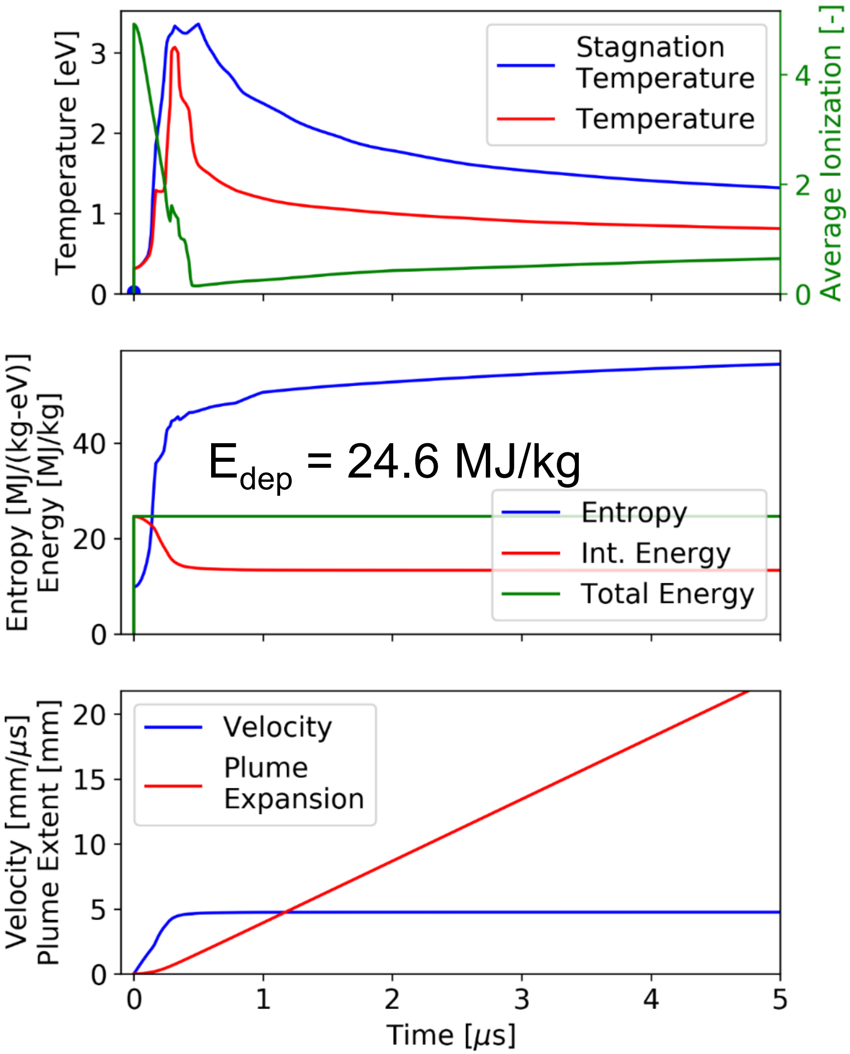
$$\left\{ \begin{array}{l} F = m\vec{a} = \frac{\mathrm{d}}{\mathrm{d}t}(m\vec{v}) \\ \Delta u = \frac{2P}{\rho d}\Delta t \end{array} \right.$$

$$E_{total} = E_{kin.} + E_{int.}$$

$$\Delta u \leq \frac{2}{\bar{u}} \left(\left. \frac{\partial s}{\partial \rho} \right|_e \right) \Delta \rho \left(\left. \frac{\partial s}{\partial e} \right|_\rho \right)^{-1}$$

Thermodynamic model matches "terminal velocity" behavior

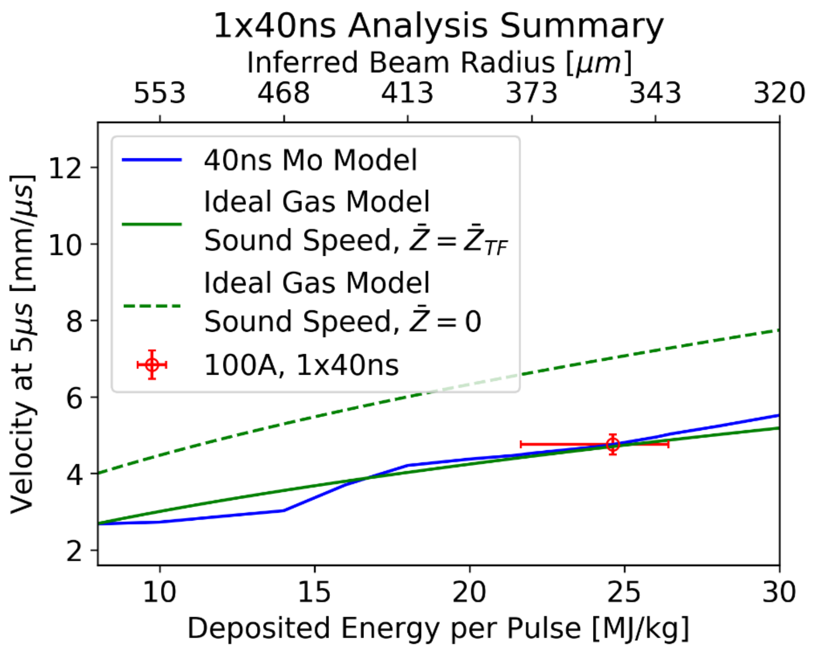
- Velocity saturates within 0.5μs (observed in experiment)
- Average ionization collapses while T increases (3-body recombination)[1]
- Provides deposited energy consistent with these assumptions
- **IS IT CORRECT? Needs measurements!**

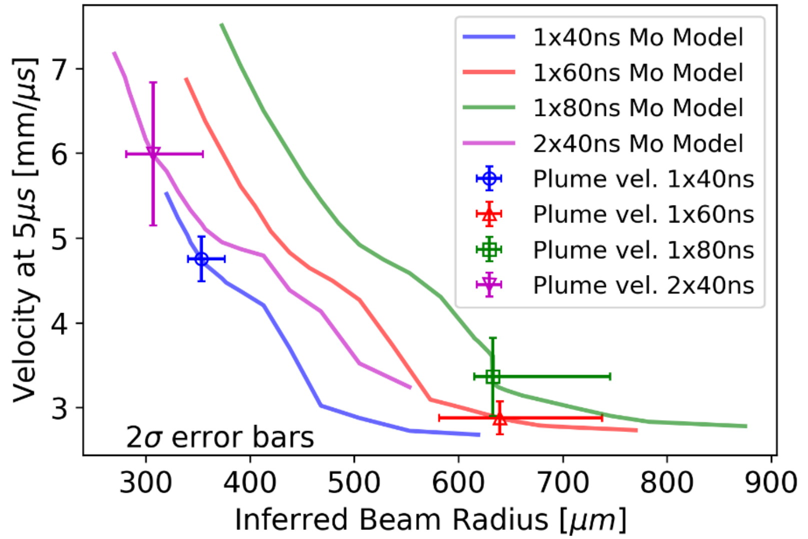


[1]cf. Rumsby and Paul, Plasma Phys. 16 (1974) 247.

Inferred spot sizes could indicate light-ion focusing effects

- Plume velocity uncertainty indicates range of E_{dep} in this model
- Axis 1 light-ion focusing effect measured with TRSS[1] showed reduction to ½ integrated spot-size
- Compare to typical parameters:
  - FWHM ~ 2 x Radius
  - MTF ~ 1.67 x FWHM
  - ~1.1mm MTF, ~2mm MTF
- **Validation of this type of model will lead to better understanding of beam-target interactions**





[1]McCuistian, et al., Proc. EPAC08 (2008) 1206.

DARHT science stations provide significant utility for LIA operations and development

- OTR-based methods provide key parameters for the envelope equation

- OTR, solenoid scans, pepper-pot all provide ways to obtain **R**, **R'**, and $\boldsymbol{\varepsilon_n}$

- Plume imaging is yielding insight into complex, late-time, target dynamics

Thank you!